Overview of NASA White Sands Test Facility Composite Overwrapped Pressure Vessel Testing

Nathanael Greene NASA-WSTF

Coauthors:

Regor Saulsberry NASA-WSTF

John Thesken, PhD. OAI-GRC

Leigh Phoenix, PhD. Cornell University

Duane Revilock NASA-GRC

Overview

- Special Thanks
- Introduction
- History of COPV Testing
- NASA-WSTF COPV Test Program
- NASA-WSTF Test Facilities
- Review of Kevlar® Testing
- Review of Carbon Testing
- General Observations

Special Thanks

Co-Authors	Affiliation	Contribution
Regor Saulsberry	NASA-WSTF	Project Manager
John Thesken, PhD.	OAI-GRC	Structural Analysis
Leigh Phoenix, PhD.	Cornell University	Modeling and Statistics
Duane Revilock	NASA-GRC	Digital Image Correlation
Reviewers	**Affiliation**	**Contribution**
Harold Beeson, PhD.	NASA-WSTF	Laboratories Office Chief
Kirk Sneddon	ARDÉ	Manufacturer Review
Special Thanks	**Affiliation**	**Contribution**
Tommy Yoder	HTSI-WSTF	Project Leader
Brad Forsyth	HTSI-WSTF	Data Analyst
Marlene Carrillo	HTSI-WSTF	Test Conductor
Steve Berko	ARDÉ	Test Consultant
COPV Team Members	Agency Wide	Test and Instrumentation Support

Introduction

- Composite overwrapped pressure vessel (COPV)
  - Typically a metallic liner overwrapped with a fiber epoxy matrix
- Weight advantage over a traditional all-metal design

wstf0106e00289

wstf0106e00088

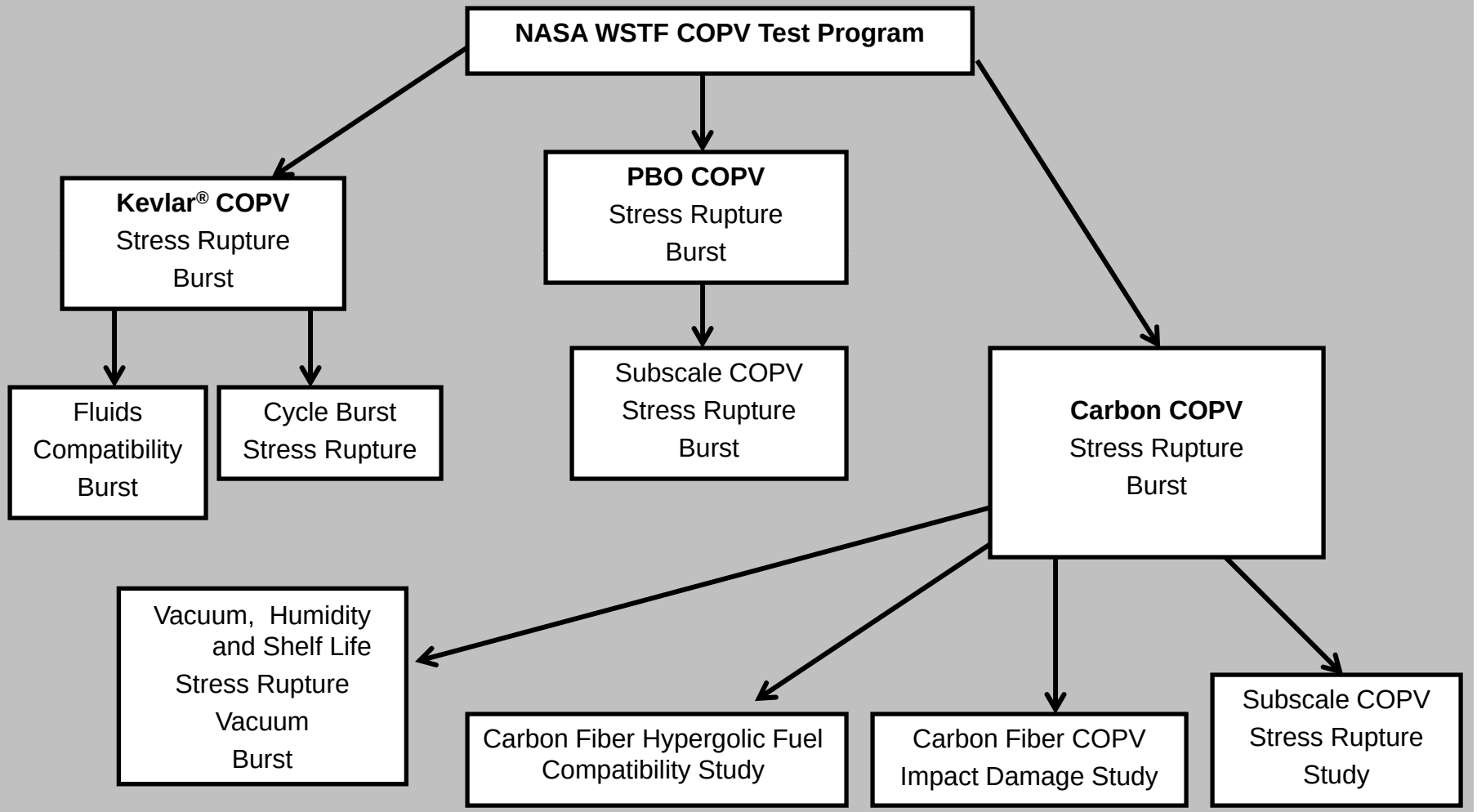
wstf1004e9252

History of COPV Testing

- NASA-GRC[1] Kevlar® COPV development (early 1970s)
- LLNL[2] Kevlar Testing of Subscale COPVs (mid 1970s)
- NASA-JSC[3] Kevlar Shuttle Transportation System (STS) Fleet Leader Program (late 1970s)
- NASA-WSTF Kevlar COPV Fluids Compatibility Testing (1990s)
- NASA-WSTF Carbon Impact Study (1990s)
- NASA-WSTF Carbon Fluids Compatibility Study (1990s)
- NASA-WSTF Subscale Carbon COPV Stress Rupture Program (1990s-current)
- NASA-WSTF STS Kevlar COPV Testing (current)
- NASA-WSTF PBO COPV Testing (1990s-current)
- NASA-WSTF Carbon COPV Shelf Life, Humidity & Vacuum Testing (buildup)

1 NASA Glenn Research Center
2 Lawrence Livermore National Laboratories
3 NASA Johnson Space Center

NASA-WSTF COPV Test Program



Stress Rupture Facilities

- New Stress Rupture Test Facility (Test Cell 862)
  - Thermally controlled
  - Backup power for data acquisition and thermal control
  - Will house 15 blast enclosures for testing up to 26-in. COPVs and one blast enclosure to house up to a 40-in. COPV

wstf1005e08438

wstf1005e08437

Stress Rupture Facilities

- Subscale COPV testing (Test Cell 270A)
- Carbon fiber and PBO COPVs currently in test

wstf0403-0562

wstf0403-0559

Stress Rupture Facilities

- Fleet leaders for ISS (Test Cell 275)
- Various flight-qualified configurations
- Eight impact-damaged COPVs on test
- Test started ~ 8 years ago

wstf01297-3817

Burst Test Facility

- Burst up to 26-in. COPVs (upgrading to burst up to 40-in. COPVs at 50 psi/s)
- Thermally controlled enclosure
- Remote data acquisition

wstf1005e08445

wstf0604e4120

Vacuum Test Facility

- Vacuum Stress Rupture Testing of COPVs
  - Thermally controlled
  - Facility in preparation for test
  - Controlled gas and humidity environment

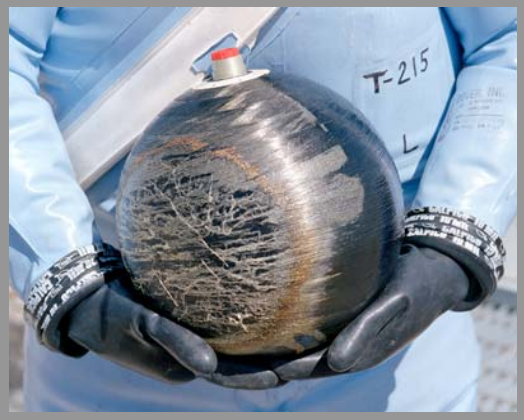
wstf0206e01036

wstf0206e01035

Fluids Compatibility

- Fluids Compatibility Testing
  - Expose COPV to fluid and burst test
  - Cryogenic fluids
  - MMH, NTO, LN_2, hydrazine, and unsymmetrical dimethylhydrazine

wstf0396-0453



wstf0496-1111

wstf0496-1109

wstf0596-1318

Pneumatic COPV Test Facility

- Pneumatic burst after mechanical impact
- 250-ft drop tower
- COPV drop testing

wstf0898-1540

wstf1295-2859

wstf09002256

Current WSTF COPV Test and Analysis Objectives

- Evaluate safe operating life remaining for Kevlar® COPVs on the Space Shuttle
  - Kevlar stress rupture life prediction model is being prepared using COPV stress rupture and strand data (Phoenix Model II)
  - Flight qualified COPV testing required to adjust parameters of the model
- Provide fleet leader data for ISS and evaluate remaining safe operating life on carbon COPVs
- Provide test data and design of future COPV applications (Constellation Program)

Kevlar Test and Analysis Objectives

- Provide flight qualified COPV test data to feed into life model
- Evaluate conservatism in current lifing numbers
  - Relate fiber strain condition with stress rupture life
  - Evaluate transverse COPV stiffness
  - Assess fiber creep with time (liner pre-stress)
  - Measure liner pre-stress
  - Record fiber strain with pressure and volume expansion
- Provide a data-validated FEA model for damage assessment

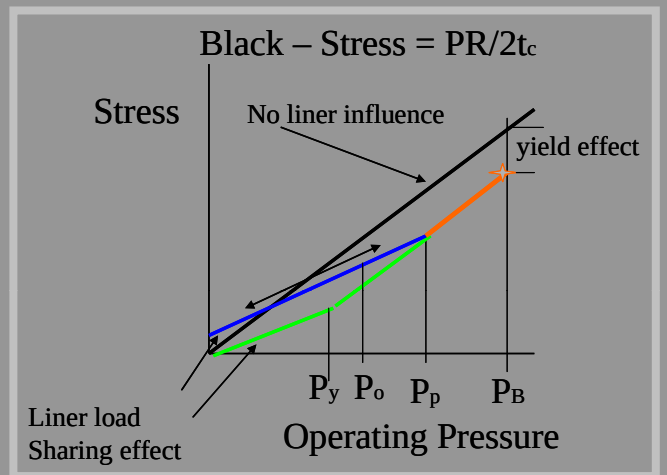
Kevlar COPV Testing

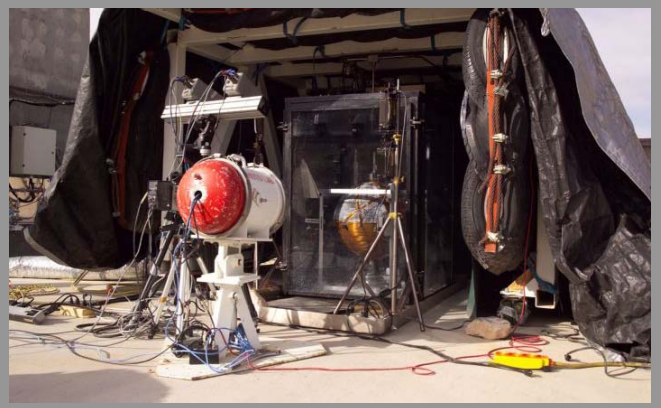
- Strain gauges
- Fiber Bragg gratings
- Acoustic emission
- Eddy current
- Volume measurement
- Girth measurement
- Digital image correlation
- Load cell
- X-ray
- Temperature, pressure

wstf1105e08998

New Measurement Development

- Volumetric strain measurement
  - Fluid input and output measurements
- Strain measurement
  - Fiber-optic Bragg gratings
- Composite thickness measurement
  - Eddie current
- Digital image correlation
  - Full field strain measurement

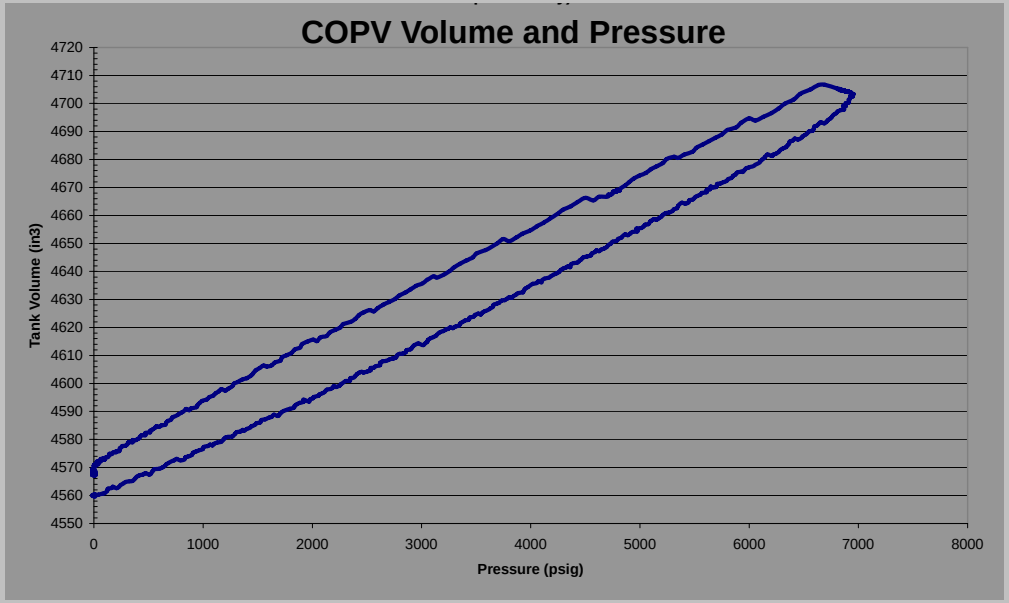




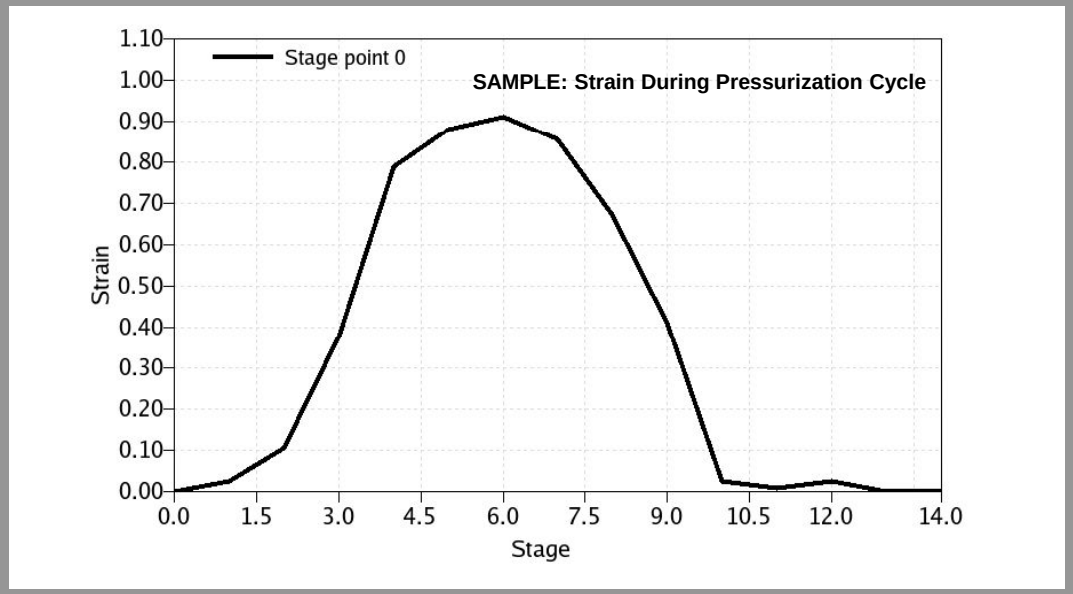
wstf0106e00249

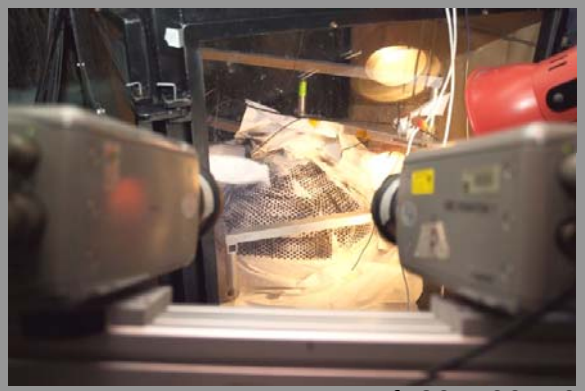
Kevlar Test Data

- Volumetric expansion with pressure
- Through-the-thickness stress gradient
- Liner pre-stress
- Evaluation of fiber creep with time
- Behavior beyond yield
- Burst volume
- Burst fiber strain

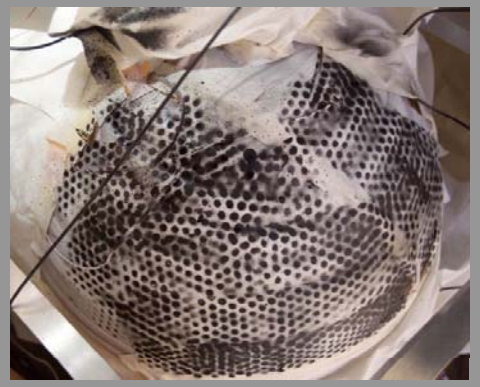


Digital Image Correlation Results





wstf1205e09446



wstf1205e09445

Pressure Cycle Captured for DIC	
Stage Number	Pressure (PSI)
0	Reference
1	250
2	1000
3	5000
4	6000
5	6450
6	6450 2 Minutes
7	6450 4 Minutes
8	4000
9	2000
10	Ambient
11	Ambient 5 Minutes
12	Ambient 25 Minutes
13	Reference
14	Reference

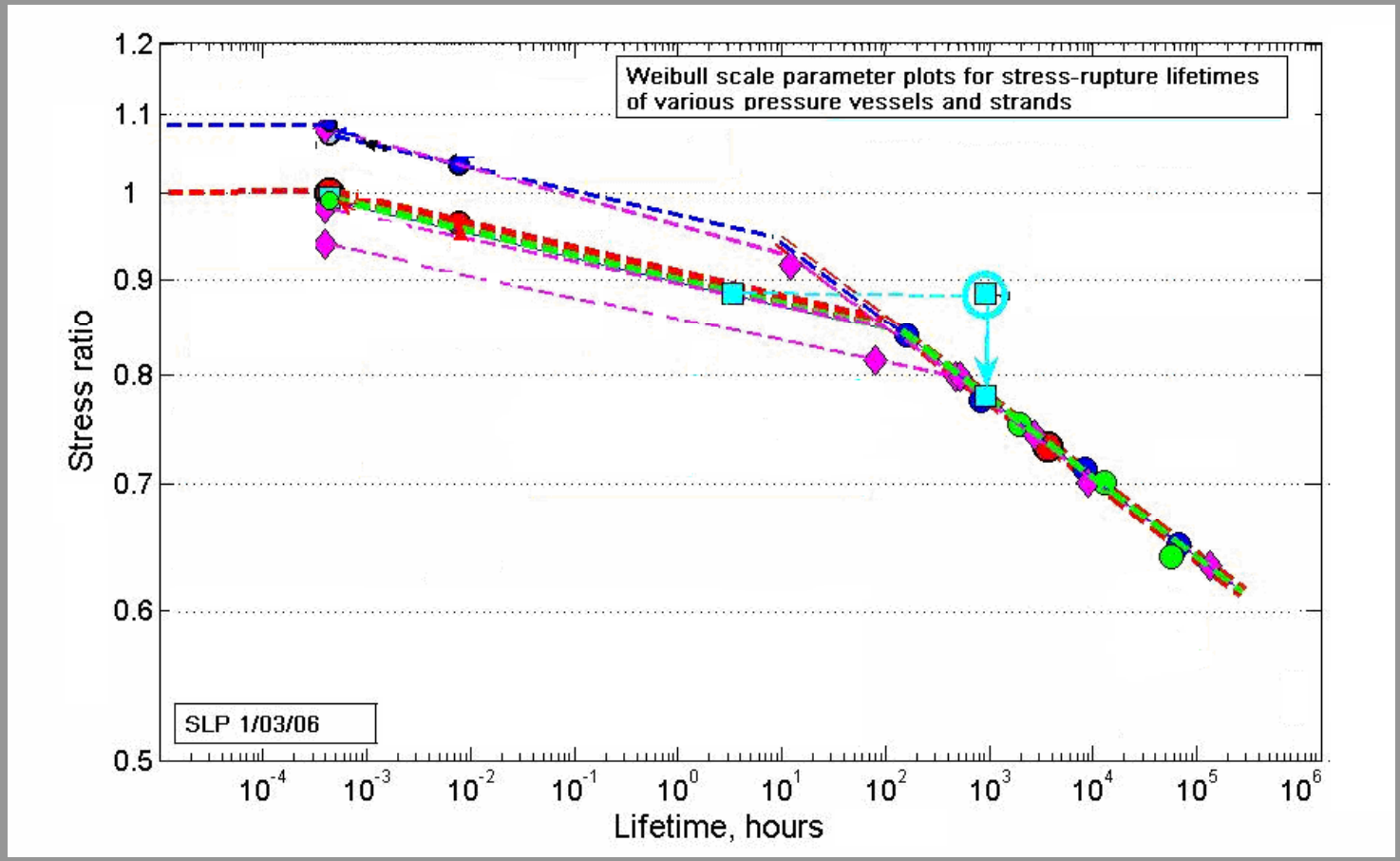
Kevlar Test Data Analysis

- Comparison of data for flight rationale
  - Scale to fiber strength
- Variables that affect fiber strength include:
  - Fiber denier, volume fraction, COPV geometry, fiber strain at autofrettage (pre-strain), UV exposure, time at pressure and temperature
- Approach for comparison
  - Evaluate differences: liner load carrying effect, volume fraction, fiber differences, time at temperature and pressure, UV exposure, impact damage, etc.

Kevlar® Test Data Analysis

- Statistical approach based on comparison of distribution of test data
  - Assume data follow a Weibull distribution
  - Comparison of data sets shown on one plot
- Small sample statistics are used
  - Small data set

Sample Kevlar® Stress Rupture Life Chart



SAMPLE: Stress Rupture Chart for Kevlar

Carbon Test and Analysis Objectives

- Provide fleet leader COPVs for ISS
- Evaluate lower-than-expected burst results for carbon subscale COPVs
- Provide stress rupture data for construction of carbon stress rupture life prediction model

Carbon Results to Date

- No new failure mode found for failures at lower-than-expected burst pressures
- Shelf life is being evaluated
  - Burst testing COPVs of different unpressurized shelf lives resulted in no significant difference in the Student's t-test
- Stress ratio calculation methods are in review
- Subscale COPVS are not flight-like
  - Minimized wrap (limit of what would be considered a COPV)
  - Less rigorous quality control than for flight COPVs
- Impact damage is a concern—was observed to reduce burst pressure

General Observations

- Understanding how stress ratios are calculated is important in evaluating remaining reliable stress rupture life
- Carbon COPVs are impact-damage sensitive and can burst before leak
- Kevlar® COPVs are more susceptible to stress rupture than carbon fiber COPVs (reflected in AIAA S-081*)

AIAA S-081-2000 Stress Rupture Requirements

Carbon Fiber	Aramid Fiber	Glass
1.5	1.65	2.25
Numbers represent the lowest fiber reinforcement stress ratio at MEOP		

* ANSI/AIAA S-081-2000, *Space Systems—Composite Overwrapped Pressure Vessels (COPVs).* American Institute of Aeronautics and Astronautics, Reston, Virginia.